

Aerosol-Cloud-Radiation Interactions in Atmospheric Forecast Models

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LONG-TERM GOALS

The long-term goal of this project is to gain a deep understanding of the role of atmospheric aerosols in affecting transmission of radiation through the atmosphere and in influencing cloud properties.

OBJECTIVES

The scientific objectives of this project are to identify the specific manner in which atmospheric aerosols determine cloud properties and to represent these interactions in atmospheric models. The technological objectives are to develop state-of-the-art instruments for aircraft sampling of aerosols that advance the long-term goals of the project.

APPROACH

The main technical approach is to conduct aircraft studies of the atmosphere, in which comprehensive sampling of atmospheric particles and radiative and cloud properties is carried out. The aircraft studies are complemented by laboratory investigations and theoretical analysis. Key individuals participating in this work are Professors John H. Seinfeld and Richard C. Flagan at the California Institute of Technology and Dr. Haf Jonsson at Naval Postgraduate School. Professor Seinfeld serves as Principal Investigator. Professor Flagan plays a key role in instrumentation development and planning of aircraft operations. As Chief Scientist of CIRPAS, Dr. Jonsson oversees all aspects of aircraft measurements and data management.

WORK COMPLETED

The major work completed this year was analysis of data from the Marine Stratocumulus Experiment (MASE) carried out in Monterey, CA during July 2005 (see 2005 annual report for more information). The figures presented in this 2006 report show some of the results of that study.

RESULTS

1. Large-Eddy simulation of marine stratocumulus

A total of 98 three-dimensional large-eddy simulations (LESs) of marine stratocumulus clouds covering both nighttime and daytime conditions were performed to explore the response of cloud optical depth (τ) to various aerosol number concentrations ($N_a = 50\text{--}2500\text{ cm}^{-3}$) and the covarying

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meteorological conditions (large-scale divergence rate and SST). The idealized First International Satellite Cloud Climatology Project (ISCCP) Regional Experiment (FIRE) and the Atlantic Stratocumulus Transition Experiment (ASTEX) Lagrangian 1 sounding profiles were used to represent the lightly and heavily drizzling cases, respectively. Through statistical analysis, τ is found to be both positively correlated with N_a and cloud liquid water path (LWP) with a higher correlation associated with LWP, which is predominantly regulated by large-scale subsidence and SST. Clouds with high LWP occur under low SST or weak large-scale subsidence. Introduction of a small amount of giant sea salt aerosol into the simulation lowers the number of cloud droplets activated, results in larger cloud droplets, and initiates precipitation for nondrizzling polluted clouds or precedes the precipitation process for drizzling clouds. However, giant sea salt aerosol is found to have a negligible effect on τ for lightly precipitating cases, while resulting in a relative reduction of τ of 3%–77% (increasing with N_a , for $N_a = 1000\text{--}2500\text{ cm}^{-3}$) for heavily precipitating cases, suggesting that the impact of giant sea salt is only important for moist and potentially convective clouds. Finally, a regression analysis of the simulations shows that the drizzle suppression is more evident in clear than polluted cases. The second indirect effect is found to enhance (reduce) the overall aerosol indirect effect for heavily (lightly) drizzling clouds; that is, τ is larger (smaller) for the same relative change in N_a than considering the Twomey (first indirect) effect alone. The aerosol indirect effect (on τ) is lessened in the daytime afternoon conditions and is dominated by the Twomey effect; however, the effect in the early morning is close but slightly smaller than that in the nocturnal run. Diurnal variations of the aerosol indirect effect should be considered to accurately assess its magnitude.

2. Evaluation of a new cloud droplet activation parameterization with in situ data from CRYSTAL-FACE and CSTRIFE

The accuracy of the 2003 prognostic, physically based aerosol activation parameterization of A. Nenes and J. H. Seinfeld (NS) with modifications introduced by C. Fountoukis and A. Nenes in 2005 (modified NS) is evaluated against extensive microphysical data sets collected on board the Center for Interdisciplinary Remotely Piloted Aircraft Studies (CIRPAS) Twin Otter aircraft for cumuliform and stratiform clouds of marine and continental origin. The cumuliform cloud data were collected during NASA's Cirrus Regional Study of Tropical Anvils and Cirrus Layers–Florida Area Cirrus Experiment (CRYSTAL-FACE, Key West, Florida, July 2002), while the stratiform cloud data were gathered during Coastal Stratocumulus Imposed Perturbation Experiment (CSTRIFE, Monterey, California, July 2003). In situ data sets of aerosol size distribution, chemical composition, and updraft velocities are used as input for the NS parameterization, and the evaluation is carried out by comparing predicted cloud droplet number concentrations (CDNC) with observations. This is the first known study in which a prognostic cloud droplet activation parameterization has been evaluated against a wide range of observations. On average, predicted droplet concentration in adiabatic regions is within ~20% of observations at the base of cumuliform clouds and ~30% of observations at different altitudes throughout the stratiform clouds, all within experimental uncertainty. Furthermore, CDNC is well parameterized using either a single mean updraft velocity \bar{w} or by weighting droplet nucleation rates with a Gaussian probability density function of w . This study suggests that for nonprecipitating warm clouds of variable microphysics, aerosol composition, and size distribution the modified NS parameterization can accurately predict cloud droplet activation and can be successfully implemented for describing the aerosol activation process in global climate models.

3. Photoacoustic insight for aerosol light absorption aloft from meteorological aircraft and comparison with particle soot absorption photometer measurements: DOE Southern Great Plains climate research facility and the Coastal Stratocumulus Imposed Perturbation Experiment (CSTRIPE)

Aerosol light absorption can be intense close to local sources such as wildland and oil fires, with smoke that disperses into the boundary layer and, with enough lift, into the upper atmosphere where it may be transported around the globe. Filter-based methods such as the Particle Soot Absorption Photometer (PSAP) are most commonly used to quantify aerosol light absorption aloft. This paper reports first measurements of aerosol light absorption aloft with photoacoustic instrumentation (PA). Three examples of aerosol light absorption are presented. The first one illustrates a case of detached layers aloft arising from intercontinental, interoceanic transport of smoke from wildland fires in Siberia to the North American continent and the measurement campaign held at the Department of Energy Atmospheric Radiation Measurement Program Climate Research Facility in north central Oklahoma. Then, two examples of intense local fire smoke light absorption from the Coastal Stratocumulus Imposed Perturbation Experiment near Marina, California, USA, are presented. The first local fire was an oil fire burning in a storage tank near Moss Landing, California, USA, and smoke from this fire was very dark, indicating a low single scattering albedo. By contrast, the second local fire was predominantly burning wood, vegetation, and structures near Fort Ord in Marina, California, USA, and the smoke was very bright, indicating a high single scattering albedo. In all examples, PA measurements at 676 nm were compared with those from a PSAP modified to measure at three wavelengths, including 660 nm.

4. Effect of aerosol number concentration on cloud droplet dispersion: A large-eddy simulation study

Through three-dimensional large-eddy simulations of marine stratocumulus we explore the factors that control the cloud spectral relative dispersion (ratio of cloud droplet spectral width to the mean radius of the distribution) as a function of aerosol number concentration and the extent to which the relative dispersion either enhances or mitigates the Twomey effect. We find that relative dispersion decreases with increasing aerosol number concentration (for aerosol number concentrations less than about 1000 cm^{-3}) because smaller droplets resulting from higher aerosol number concentrations inhibit precipitation and lead to (1) less spectral broadening by suppressed collision and coalescence processes and (2) more spectral narrowing by droplet condensational growth at higher updraft velocity because reduced drizzle latent heating at cloud top results in increased boundary layer turbulent kinetic energy production by buoyancy and thereby stronger turbulence. Increased spectral broadening owing to increased cloud-top entrainment mixing, also as a result of increased boundary layer turbulence, is relatively insignificant compared with outcomes 1 and 2. The coefficient k , an important parameter that relates cloud droplet effective radius and volume mean radius in large-scale models, is a function of skewness and relative dispersion of the distribution and is negatively correlated with relative dispersion. Increasing k with increasing aerosol number concentration leads to maximum enhancement of the cloud susceptibility (the change of cloud optical depth due to change of cloud droplet number concentration) over that attributable to the Twomey effect alone by about 4.2% and 39% for simulated FIRE and ASTEX cases, respectively.

5. Marine Stratocumulus Experiment

The MASE field campaign was undertaken in July 2005 off the coast of Monterey, California to evaluate aerosol-cloud relationships in the climatically important regime of eastern Pacific marine stratocumulus. Thirteen clouds sampled in the region 123.5-121.5 W and 35.75 – 36.75 N were selected for detailed analysis; sub-cloud aerosol number concentrations varied from 70 to 1300 cm⁻³, with some cases exhibiting ship-tracks. Among the clouds sampled, that observed on July 5 was impacted by a ship-track, as confirmed by in situ aircraft measurements and GOES near-IR satellite imagery. Multiple airborne horizontal traverses (~30 km) through the ship-track and unperturbed regions provide insights into variations of cloud properties on a 50 m (~1 Hz) scale both horizontally and vertically. Comparison of ship-track and clean regions shows that the ship-track region exhibited a smaller cloud drop effective radius, reduced drizzle drop number concentration, and larger cloud LWC than the adjacent clean regions. The ship-track region also exhibits a smaller cloud drop spectral width and relative dispersion, in accord with LES predictions of *Lu and Seinfeld [2006]* based on meteorological conditions in the ASTEX and FIRE experiments. LES simulations of the July 5 cloud were undertaken; cloud top and base altitudes, vertical profiles of cloud drop effective radius, cloud LWC, drizzle drop number concentration and mean size, precipitation rate, cloud drop spectral width and relative dispersion, and the variations of these parameters between the ship-track and clean regions were simulated reasonably well. Discrepancies do exist between observations and LES predictions: drizzle drop mean radius is overestimated, drizzle drop number concentration is underestimated, and precipitation rate is overestimated. Despite using a fine (5 m) vertical resolution near the MBL inversion, the simulations produce evidence of numerical over-entrainment, resulting in a larger cloud drop spectral width and relative dispersion near cloud top than those observed. The overall average of aerosol and cloud conditions over the 13 cloud regions sampled were also computed.

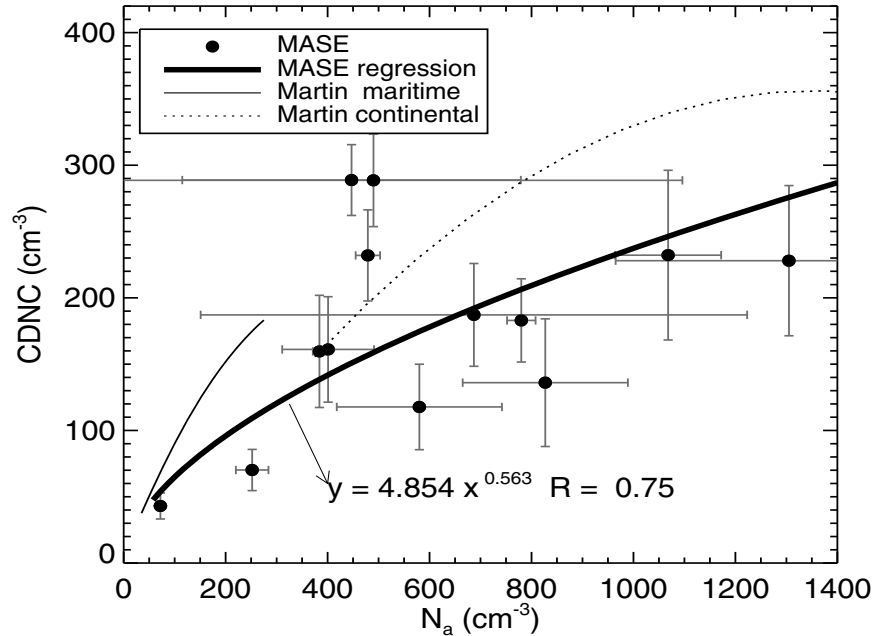


Figure 1. Relationship between cloud droplet number concentration and below-cloud aerosol number concentration. Error bar represents the standard deviation about the mean. The thick solid line is the power-law fit to the data. The thin solid and dotted lines are from Martin et al. [1994] for maritime and continental stratocumuli, respectively.

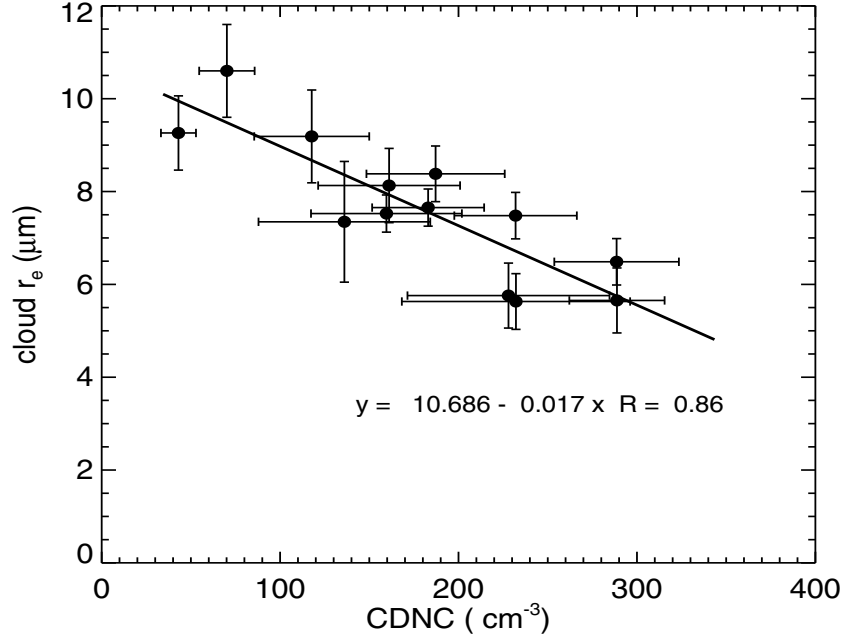


Figure 2. Cloud effective radius versus cloud droplet number concentration. Error bar represents the standard deviation about the mean. Solid line is the linear fit through all clouds.

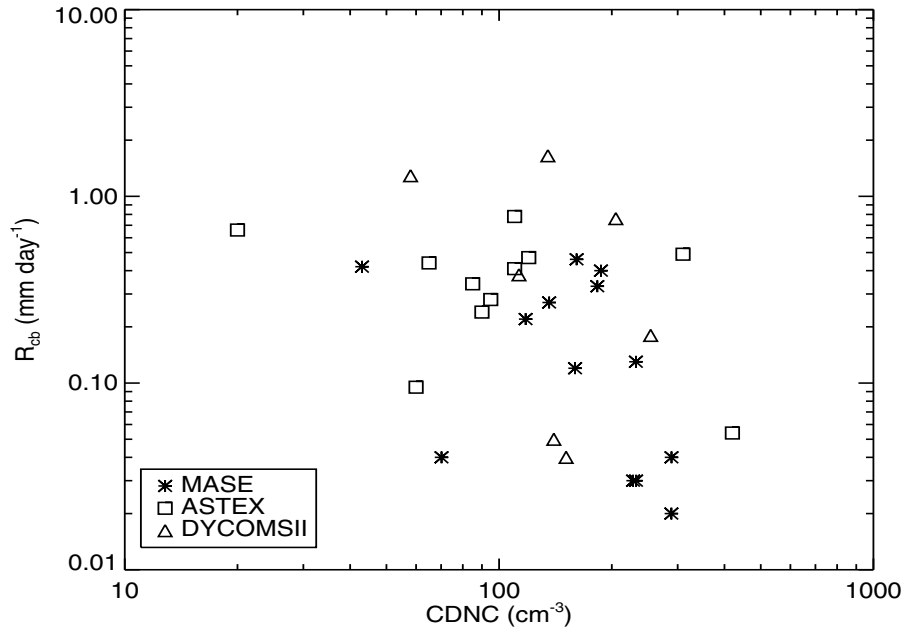


Figure 3. Cloud base drizzle rate (R_{CB}) versus cloud droplet number concentration. ASTEX and DYCOMS II data are from Wood [2005] and van Zanten et al. [2005], respectively.

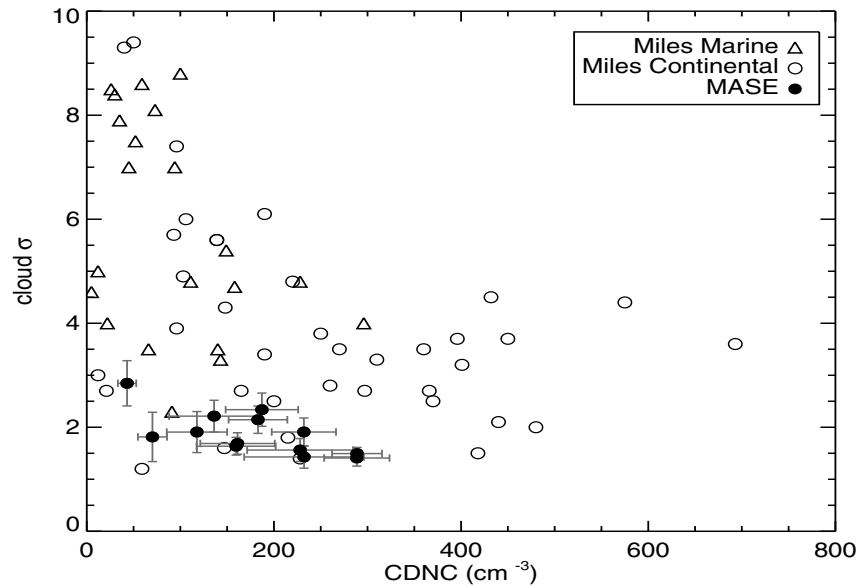


Figure 4. Cloud drop spectral width versus cloud droplet number concentration. MASE \square is averaged over the upper third of the cloud depth. Marine and Continental data are observations of stratiform clouds compiled in Miles et al. [2000], and those data far from cloud top are removed to be consistent.

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